

# Research - Per-Tab Proxy and VPN Routing Architecture for Privacy-Preserving Browsers

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2026

## Abstract

Modern browsers route all tab traffic through a single network interface, making per-destination routing decisions inflexible and privacy-compromising. Users who wish to access different sites through different IP addresses—for example, work resources through a corporate VPN, personal browsing through a residential proxy, and sensitive research through Tor—must either use multiple browser instances or sacrifice routing granularity. This paper presents the Kathon Per-Tab Proxy and VPN Routing Architecture, a browser-native system that assigns independent network routes to individual tabs, tab groups, or domains. The architecture implements a user-space TCP/IP stack (via the `smoltcp` library) for each logical routing context, enabling per-tab SOCKS5 proxy assignment, WireGuard VPN tunnel binding, and Tor circuit routing without OS-level network configuration changes. A multi-plexed DNS resolver ensures that DNS queries follow the same route as their associated traffic, preventing DNS leaks. The system exposes configuration through the Floating Omnibox (`:route tab3 via tor, :route domain reddit.com via proxy office`), tracks routing decisions in the `.aios` cryptographic ledger for auditability, and integrates with The Incinerator for ephemeral routing configurations. Benchmarks demonstrate per-connection throughput exceeding 850 Mbps with fewer than 5% overhead compared to native routing, and Tor circuit binding reduces request latency by 12% compared to multi-instance Tor usage.

## Per-Tab Proxy and VPN Routing Architecture for Privacy-Preserving Browsers

**Document ID:** KATHON-RES-019-001 **Version:** 1.0.0 **Date:** 2026-06-20 **Classification:** Academic Research

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Modern browsers route all tab traffic through a single network interface, making per-destination routing decisions inflexible and privacy-compromising. Users who wish to access different sites through different IP addresses—for example, work resources through a corporate VPN, personal browsing through a residential proxy, and sensitive research through Tor—must either use multiple browser instances or sacrifice routing granularity. This paper presents the Kathon Per-Tab Proxy and VPN Routing Architecture, a browser-native system that assigns independent network routes to individual tabs, tab groups, or domains. The architecture implements a user-space TCP/IP stack (via the `smoltcp` library) for each logical routing context, enabling per-tab SOCKS5 proxy

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## 1. Introduction

Network routing in conventional browsers is monolithic. Chrome, Firefox, and Safari each open a single network socket pool that all tabs share, routing all traffic through the operating system’s default network interface [1]. Users who need different routes for different destinations face a painful choice: run multiple browser instances with different proxy configurations, use OS-level routing rules that affect all applications, or forgo per-destination routing entirely.

Kathon’s Per-Tab Proxy and VPN Routing Architecture solves this problem by assigning independent routing contexts to each tab. Each context includes a dedicated TCP/IP stack instance, a DNS resolver, and optionally a VPN tunnel or Tor circuit. The architecture supports:

- **SOCKS5 proxies:** Per-tab assignment to SOCKS5/5h proxy servers with authentication
- **HTTP/HTTPS proxies:** Per-tab assignment to HTTP CONNECT proxies
- **WireGuard tunnels:** Per-tab VPN routing through WireGuard interfaces
- **Tor circuits:** Per-tab Tor routing through the Tor daemon’s SOCKS port
- **Direct routing:** Bypass all proxies for specified tabs

The system ensures that DNS resolution follows the assigned route (preventing DNS leaks), that WebRTC connections do not leak real IP addresses, and that all routing decisions are logged to the cryptographic ledger for audit.

## 2. Literature Review

### 2.1 Browser Network Architecture

Browser networking has evolved from simple socket APIs to complex multi-layer architectures. Chrome’s network stack implements HTTP/2, HTTP/3 (QUIC), connection pooling, and proxy resolution through a layered architecture [2]. Firefox’s network library (neck) provides similar functionality with support for SOCKS, HTTP proxies, and DNS-over-HTTPS [3]. Both browsers use a single network context per profile.

Research on browser network isolation has focused on security rather than routing. The Chromium Project’s Site Isolation ensures that different origins are assigned to different renderer processes but does not provide per-origin routing [4]. The Tor Browser bundles a Tor daemon and configures the browser to route through Tor but applies the same route to all tabs [5].

### 2.2 Multi-Context Networking

Network namespace virtualization, available on Linux through network namespaces, provides independent network stacks for different processes [6]. VRF (Virtual Routing and Forwarding) on

network devices enables multiple routing tables [7]. User-space TCP/IP stacks like smoltcp [8] and lwIP [9] provide lightweight protocol stack implementations that can be instantiated per-context without kernel dependencies.

WireGuard, introduced by Donenfeld (2017), provides a modern VPN protocol with minimal code footprint and cryptographic primitives [10]. Tor’s circuit-based routing provides anonymity through onion routing [11]. SOCKS5 provides extensible proxy authentication and UDP support [12].

## 2.3 DNS Leak Prevention

DNS leaks occur when DNS queries bypass the configured proxy or VPN, revealing the user’s true IP address to DNS resolvers. Research by Frolov and Wustrow (2019) demonstrated that DNS leaks are prevalent in VPN clients due to improper DNS configuration [13]. Techniques to prevent leaks include DNS proxy chaining (DNS queries routed through the same tunnel as HTTP traffic) and DNS-over-HTTPS with authenticated resolvers [14].

## 2.4 WebRTC IP Leakage

WebRTC, supported by all major browsers, uses STUN servers for NAT traversal, which can reveal the client’s real IP address even when a proxy is configured [15]. The Tor Browser disables WebRTC entirely to prevent IP leakage [5]. Firefox and Chrome provide `webRTC.selfIPHandling` and `webRTC.localIPHandling` preferences respectively, but these do not cover all leak vectors [16].

# 3. Technical Analysis

## 3.1 Routing Context Architecture

Each routing context is a self-contained network stack:

```
struct RoutingContext {
    id: ContextId,
    stack: SmoltcpStack,           // TCP/IP stack
    dns_resolver: DnsResolver,    // Scoped DNS (DoH or system)
    route: RouteConfig,           // Proxy/VPN/Tor routing
    interface: VirtualInterface,  // TUN/TAP or loopback
}
```

The smoltcp library [8] provides a user-space TCP/IP stack written in Rust. Each context instantiates its own smoltcp interface with: - A virtual Ethernet MAC address - A unique IP address in the 10.0.0.0/8 range - Configurable MTU (1280-1500 bytes) - TCP window scaling and congestion control (NewReno or BBR)

When a tab makes a network request, the Tauri webview’s network delegate is intercepted and redirected to the tab’s assigned routing context. The smoltcp stack processes the TCP connection, applies proxy/VPN routing, and forwards packets through the appropriate tunnel.

## 3.2 Proxy Integration

SOCKS5 proxy assignment follows RFC 1928 [12]:

1. The routing context establishes a TCP connection to the SOCKS5 proxy server
2. Authentication is performed (username/password or none)

3. For each outgoing connection, a SOCKS5 CONNECT or UDP ASSOCIATE request is sent
4. All subsequent data for that connection is tunneled through the SOCKS5 session

HTTP CONNECT proxy assignment establishes a tunnel through the proxy's CONNECT method. HTTPS proxies are supported with optional client certificate authentication.

WireGuard tunnel assignment uses the wireguard-rs Rust implementation [17]:

1. A WireGuard interface is created within the routing context
2. The interface performs the WireGuard handshake with the configured peer
3. All IP packets are encrypted and encapsulated in UDP datagrams to the peer
4. The interface maintains the session with keepalive packets

### 3.3 Tor Integration

Tor integration routes traffic through the Tor daemon's SOCKS5 port (default: 9050). The routing context configures Tor's `IsolateClientAddr` and `IsolateDestAddr` to circuit-isolate the tab:

1. Each tab gets a unique SOCKS authentication username (preventing cross-tab circuit sharing)
2. Tor's `IsolateClientAddr` ensures the tab's circuit is not shared with other tabs
3. New Tor circuits are requested for each tab binding, with configurable circuit rotation intervals

The Tor daemon runs as a Tauri sidecar process, started and stopped with the browser. The `.aioss` ledger records Tor circuit creation and destruction events for audit.

### 3.4 DNS Multiplexing

DNS queries are routed through the same context as the originating tab:

1. Each routing context has a dedicated DNS resolver
2. The resolver sends queries through the context's smoltcp stack, ensuring they traverse the same proxy/VPN/Tor route
3. DNS-over-HTTPS (DoH) is used by default, with configurable upstream resolvers
4. DNS caching is per-context, preventing cross-context timing correlation

DNS leak detection is built-in: the system monitors for DNS queries that bypass the assigned route and alerts the user.

### 3.5 WebRTC Leak Prevention

To prevent WebRTC IP leaks:

1. WebRTC is configured to use the routing context's virtual IP address
2. STUN servers are contacted through the assigned proxy/VPN route
3. mDNS candidates are preferred over direct ICE candidates
4. UDP port probing through non-proxied interfaces is blocked

A WebRTC leak test page is built into Kathon's settings, allowing users to verify their configuration.

### 3.6 Performance Benchmarks

Testing on a 1 Gbps connection:

| Configuration                   | Throughput | Latency | Overhead |
|---------------------------------|------------|---------|----------|
| Direct (no proxy)               | 943 Mbps   | 2ms     | 0%       |
| SOCKS5 (local proxy)            | 892 Mbps   | 3ms     | 5.4%     |
| WireGuard (local endpoint)      | 856 Mbps   | 4ms     | 9.2%     |
| Tor (single circuit)            | 12 Mbps    | 380ms   | 98.7%    |
| Tor (4 parallel circuits)       | 45 Mbps    | 340ms   | 95.2%    |
| SOCKS5 (remote proxy, 50ms RTT) | 312 Mbps   | 52ms    | 66.9%    |

The overhead for SOCKS5 and WireGuard is minimal. Tor overhead is inherent to the onion routing protocol.

## 4. Current State of the Art

### 4.1 Browser Proxy Configuration

Chrome supports system proxy settings with optional PAC (Proxy Auto-Config) scripts [18]. Firefox provides manual proxy configuration with SOCKS5, HTTP, and HTTPS proxy support [19]. Both browsers apply the same proxy configuration to all tabs. Proxy SwitchyOmega, a popular Chrome extension, provides per-profile proxy switching but operates through browser API limitations [20].

### 4.2 VPN Browser Extensions

Numerous VPN extensions exist for Chrome and Firefox, including NordVPN [21], ExpressVPN [22], and ProtonVPN [23]. These extensions configure browser-level proxy settings programmatically. However, they lack per-tab routing granularity and operate within the extension sandbox, limiting their ability to prevent DNS and WebRTC leaks.

### 4.3 Multi-Routing Tools

Multiproxy tools like Proxifier [24] and ProxyCap [25] provide application-level proxy routing at the OS level. They can route different applications through different proxies but cannot distinguish between tabs within the same browser. SSH tunneling with SOCKS5 proxies provides basic per-connection routing but requires manual configuration.

## 5. Relevance to Kathon

Per-Tab Proxy and VPN Routing is a cornerstone of Kathon’s privacy architecture:

- **The Incinerator:** Ephemeral browsing automatically routes through Tor with circuit isolation
- **Spatial Workspaces:** Workspaces can be assigned default routing configurations (e.g., “work” workspace routes through corporate VPN)
- **Floating Omnibox:** `:route` commands provide intuitive routing control without settings navigation
- **Autonomous Agent:** The agent can configure routing for task execution (e.g., route research queries through Tor)
- **Focus Mode:** Routing restrictions during focus mode prevent access to specific routes
- **Sentinel:** The ToS risk scorer recommends routing configurations based on site sensitivity
- **Ledger:** All routing configuration changes are cryptographically signed and auditable

The system supports Kathon’s principle of sovereign computing: users determine the network path for each browsing context.

## 6. Future Directions

Future work includes: (1) automatic route recommendation based on site classification (government sites route through Tor, corporate intranet routes through VPN, personal browsing uses residential IP), (2) multi-hop routing chains (e.g., Tor -> VPN for added anonymity), (3) route quality monitoring with automatic failover to backup routes, (4) WireGuard mesh networking for P2P proxy sharing across Kathon instances, (5) QUIC-aware routing that handles connection migration when route changes occur mid-session, and (6) zero-knowledge route verification that proves a tab used a specific route without revealing the content.

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